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(54) Title: DszD UTILIZATION IN DESULFURIZATION OF DBT BY RHODOCOCCUS sp. IGTS8

(57) Abstract

The invention relates to the discovery that the rate of reaction of the desulfurization of fossil fuels is enhanced by the addition of an oxidoreductase to the biocatalyst. The invention is drawn to a method for enhancing the rate of desulfurizing a fossil fuel containing organic sulfur compounds, comprising the steps of: a) contacting the fossil fuel with an aqueous phase containing a biocatalyst capable of cleaving carbon-sulfur bonds and a rate-enhancing amount of an oxidoreductase, thereby forming a fossil fuel and aqueous phase mixture; b) maintaining the mixture of step (a) under conditions sufficient for cleavage of the carbon-sulfur bonds of the organic sulfur molecules by the biocatalyst, thereby resulting in a fossil fuel having a reduced organic sulfur content; and c) separating the fossil fuel having a reduced organic sulfur content from the resulting aqueous phase. The invention also relates to a recombinant microorganism containing one or more recombinant DNA molecules which encode a biocatalyst capable of desulfurizing a fossil fuel containing organic sulfur molecules and which encode an oxidoreductase. The invention also relates to a composition comprising (a) a biocatalyst capable of desulfurizing a fossil fuel containing organic sulfur molecules and (b) an oxidoreductase.

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DszD UTILIZATION IN DESULFURIZATION OF DBT BY *Rhodococcus* sp. IGTS8

BACKGROUND OF THE INVENTION

The microbial desulfurization of fossil fuels has been an area of active investigation for over fifty years. The object of these investigations has been to develop biotechnology based methods for the pre-combustion removal of sulfur from fossil fuels, such as coal, crude oil and petroleum distillates. The driving forces for the development of desulfurization methods are the increasing levels of sulfur in fossil fuel and the increasingly stringent regulation of sulfur emissions. Monticello *et al.*, "Practical Considerations in Biodesulfurization of Petroleum," IGT's 3d Intl. Symp. on Gas, Oil, Coal and Env. Biotech., (Dec. 3-5, 1990) New Orleans, LA.

Many biocatalysts and processes have been developed to desulfurize fossil fuels, including those described in U.S. Patent Nos. 5,356,801, 5,358,870, 5,358,813, 5,198,341, 5,132,219, 5,344,778, 5,104,801 and 5,002,888, incorporated herein by reference. Economic analyses indicate that one limitation in the commercialization of the technology is improving the reaction rates and specific activities of the biocatalysts, such as the bacteria and enzymes that are involved in the desulfurization reactions. The reaction rates and specific activities (sulfur removed/hour/gram of biocatalyst) that have been reported in the literature are much lower than those necessary for optimal commercial technology. Therefore, improvements in the longevity and specific activity of the biocatalyst are desirable.

SUMMARY OF THE INVENTION

The invention relates to the discovery that a class of proteins, one of which was recently purified from *Rhodococcus* sp. IGTS8, activates two monooxygenases (DszC and DszA) involved in the desulfurization of fossil fuels. Neither DszC nor A are enzymatically active when purified to homogeneity; however, upon the addition of this additional protein (designated DszD herein), enzymatic activity is restored. The function of this protein is believed to couple the oxidation of NADH with the oxygenation of the substrate molecule. A search of the sequence databases revealed that DszD is equivalent to another recently identified *Rhodococcus* protein, ThcE, which is induced by growth in the presence of atrazine, thiocarbamate herbicides and primary alcohols. Based upon sequence similarity, ThcE appears to be a member of the group III alcohol dehydrogenases, or oxidoreductases, designated alcohol: N,N'-dimethyl-3-nitrosoaniline oxidoreductases. DszD has a monomer molecular weight of approximately 50,000 (by SDS-PAGE) but behaves as a multimeric protein (decamer) on HPLC size exclusion chromatography. The activation of DszC and A by DszD follows saturation kinetics.

Thus, the invention relates to the discovery that the rate of microbial desulfurization of fossil fuels is enhanced or activated by or dependent upon the addition of an oxidoreductase to the biocatalyst or reaction medium. The invention is drawn to a method for enhancing the rate of desulfurizing a fossil fuel containing organic sulfur compounds, comprising the steps of:

a) contacting the fossil fuel with an aqueous phase containing a biocatalyst or biocatalysts capable of cleaving carbon-sulfur bonds (such as Dsz A, Dsz B and/or Dsz C) and a rate-enhancing amount of an oxidoreductase, thereby forming a fossil fuel and aqueous phase mixture;

b) maintaining the mixture of step (a) under conditions sufficient for cleavage of the carbon-sulfur bonds of the organic sulfur molecules by the biocatalyst, thereby resulting in a fossil fuel having a reduced organic sulfur content; and

c) separating the fossil fuel having a reduced organic sulfur content from the resulting aqueous phase.

The invention also relates to enhancing the rate of the reaction catalyzed by DszA and/or DszC with a rate enhancing amount of oxidoreductase. This can be accomplished, for example, by adding the oxidoreductase to a biocatalyst or by causing expression or overexpression of the oxidoreductase in a biocatalyst.

In yet another embodiment, the invention relates to a recombinant microorganism containing one or more recombinant DNA molecules which encode a biocatalyst capable of catalyzing one or more steps in a process for desulfurizing a fossil fuel containing organic sulfur molecules and which encode an oxidoreductase.

The invention includes a composition comprising (a) a biocatalyst capable of catalyzing one or more steps in a process for desulfurizing a fossil fuel containing organic sulfur molecules and (b) an oxidoreductase.

BRIEF DESCRIPTION OF THE DRAWINGS

Figure 1 is a graphic illustration of DszC and A activity after ion exchange chromatography. DszC (15 μg) was added to each fraction and tested for conversion from DBT to DBTO and DBTO2. DszA (5 μg) was added to each fraction and tested for DBT sultone to BHBP conversion. Endogenous DszC activity was also tested.

Figure 2 is a graphic illustration of DszC activity after Superdex 75 size exclusion chromatography. DszC (15 μg) was added to each fraction and tested for conversion

from DBT to DBTO2. DszA activity after Superdex 75 size exclusion chromatography. DszA (5 μg) was added to each fraction and tested for DBTsultone to BHBP conversion.

Figure 3 is an electrophoretic gel illustrating SDS-PAGE (14% acrylamide) of the purification of DszD. Lane 1 presents the molecular weight standards (Biorad, 200, 116, 97.4, 66, 45, 31, 21.5 and 14.5 kDa); lane 2, crude cell lysate; lane 3, after Q-sepharose; lane 4, after Toyopearl-DEAE; lane 5, after MonoQ, and; lane 6, after Superdex 75.

Figure 4 illustrates the activation of DszC by the addition of increasing amounts of DszD. A fixed amount of DszC (0.33 nmol)) was titrated with increasing amounts of DszD.

Figure 5 illustrates activation of DszA by increasing amounts of DszD. A fixed amount of DszA (0.16 nmol) was titrated with increasing amounts of DszD.

Figure 6 sets forth the DNA sequence and putative amino acid sequence of the ThcE (DszD) gene.

DETAILED DESCRIPTION OF THE INVENTION

In the petroleum extraction and refining arts, the term "organic sulfur" is generally understood as referring to organic molecules having a hydrocarbon framework to which one or more sulfur atoms (called heteroatoms) are covalently joined. These sulfur atoms can be joined directly to the hydrocarbon framework, e.g., by one or more carbon-sulfur bonds, or can be present in a substituent joined to the hydrocarbon framework of the molecule, e.g., a sulfate group. The general class of organic molecules having one or more sulfur heteroatoms are referred to as "organosulfur compounds". The hydrocarbon portion of these compounds can be aliphatic, aromatic, or partially aliphatic and partially aromatic.

Cyclic or condensed multicyclic organosulfur compounds in which one or more sulfur heteroatoms are linked directly

or indirectly to adjacent carbon atoms in the hydrocarbon framework by aromatic carbon-sulfur bonds are referred to as "sulfur-bearing heterocycles". The sulfur that is present in many types of sulfur-bearing heterocycles is referred to as "thiophenic sulfur" in view of the five-membered aromatic ring in which the sulfur heteroatom is present. The simplest such sulfur-bearing heterocycle is thiophene, which has the composition C4H4S.

Sulfur-bearing heterocycles are known to be stable to conventional desulfurization treatments, such as hydrodesulfurization (HDS). Sulfur-bearing heterocycles can have relatively simple or relatively complex chemical structures. In complex heterocycles, multiple condensed aromatic rings, one or more of which can be heterocyclic, are present. The difficulty of desulfurization increases with the structural complexity of the molecule. That is, refractory behavior is most accentuated in complex sulfur-bearing heterocycles, such as dibenzothiophene (DBT, C12H8S).

DBT is a sulfur-bearing heterocycle that has a condensed, multiple aromatic ring structure in which a five-membered thiophenic ring is flanked by two six-membered benzylic rings. Much of the residual post-HDS organic sulfur in fossil fuel refining intermediates and combustible products is thiophenic sulfur. The majority of this residual thiophenic sulfur is present as DBT and derivatives thereof having one or more alkyl or aryl groups attached to one or more carbon atoms present in one or both flanking benzylic rings. DBT itself is accepted in the relevant arts as a model compound illustrative of the behavior of the class of compounds encompassing DBT and derivatives thereof in reactions involving thiophenic sulfur. Monticello and Finnerty, *Annual Reviews in Microbiology* 39:371-389 (1985) at 372-373. DBT and derivatives thereof can account for a significant percentage of the total sulfur content of

particular crude oils, coals and bitumen. For example, these sulfur-bearing heterocycles have been reported to account for as much as 70 wt% of the total sulfur content of West Texas crude oil, and up to 40 wt% of the total sulfur content of some Middle East crude oils. Thus, DBT is considered to be particularly relevant as a model compound for the forms of thiophenic sulfur found in fossil fuels, such as crude oils, coals or bitumen of particular geographic origin, and various refining intermediates and fuel products manufactured therefrom. *Id.* Another characteristic of DBT and derivatives thereof is that, following a release of fossil fuel into the environment, these sulfur-bearing heterocycles persist for long periods of time without significant biodegradation. Gundlach *et al.* *Science 221*:122-129 (1983). It is, therefore, desirable to remove these organosulfur compounds from fossil fuels or other carbonaceous materials which contain them.

A fossil fuel or carbonaceous material that is suitable for desulfurization treatment according to the present invention is one that contains organic sulfur. Such a fossil fuel is referred to as a "substrate fossil fuel". Substrate fossil fuels that are rich in thiophenic sulfur are particularly suitable for desulfurization according to the method described herein. Examples of such substrate fossil fuels include Cerro Negro or Orinoco heavy crude oils; Athabascan tar and other types of bitumen; petroleum refining fractions such as light cycle oil, heavy atmospheric gas oil, and No. 1 diesel oil; and coal-derived liquids manufactured from sources such as Pocahontas #3, Lewis-Stock, Australian Glencoe or Wyodak coal.

Biocatalytic desulfurization, or BDS, is the excision, liberation or removal of sulfur from organosulfur compounds, including refractory organosulfur compounds such as sulfur-bearing heterocycles, as a result of the oxidative cleavage (preferably selectively) of carbon-sulfur bonds in said

compounds by a biocatalyst. BDS treatment yields the desulfurized hydrocarbon framework of the former refractory organosulfur compound, along with inorganic sulfur substances which can be readily separated from each other by known techniques such as fractional distillation or water extraction. For example, DBT is "converted" into hydroxybiphenyl when subjected to BDS treatment.

BDS is carried out by biocatalyst(s). Biocatalysts include one or more non-human organisms (e.g., recombinant and non-recombinant, viable and non-viable microorganisms) that functionally express one or more enzymes that direct, singly or in concert with each other, the removal of sulfur from organosulfur compounds, including sulfur-bearing heterocycles, by the oxidation of sulfur and/or the cleavage of carbon-sulfur bonds in said compounds; one or more enzymes obtained from such organisms; or a mixture of such organisms and enzymes. Organisms that exhibit one or more biocatalytic activities required for the desulfurization of a fossil fuel or other carbonaceous material are referred to herein as being Dsz+. Organisms that lack such a biocatalytic activity are referred to herein as being Dsz-. A "biocatalyst" is defined herein as a biological material, or a material of biological origin, which possesses the ability to catalyze one or more reactions, in the presence of appropriate co-factors and/or co-enzymes, for example.

The invention relates to the improved removal of sulfur from carbonaceous materials, such as fossil fuels, containing organic sulfur molecules comprising adding a rate-enhancing amount of an oxidoreductase to the biocatalyst capable of desulfurizing the carbonaceous material.

The biocatalysts employed herein are, generally, known in the art. Several investigators have reported the genetic modification of naturally-occurring bacteria into mutant strains capable of catabolizing DBT. Kilbane, J.J., Resour.

Cons. Recycl. 3:69-79 (1990), Isbister, J.D., and R.C. Doyle, U.S. Patent No. 4,562,156 (1985), and Hartdegan, F.J. *et al.*, Chem. Eng. Progress 63-67 (1984). Many of these mutants desulfurize DBT nonspecifically. Thus, a portion of the fuel value is lost through this microbial action. Isbister and Doyle reported the derivation of a mutant strain of *Pseudomonas* which appeared to be capable of selectively liberating sulfur from DBT.

Kilbane has reported the mutagenesis of a mixed bacterial culture, thereby producing a bacterium which is capable of selectively liberating sulfur from DBT by an oxidative pathway. This culture was composed of bacteria which can be obtained from natural sources, such as sewage sludge, petroleum refinery wastewater, garden soil, coal, tar-contaminated soil, etc., and maintained in culture under conditions of continuous sulfur deprivation in the presence of DBT. The culture was then exposed to the chemical mutagen 1-methyl-3-nitro-1-nitrosoguanidine. The major catabolic product of DBT metabolism by this mutant culture was hydroxybiphenyl; sulfur was released as inorganic water-soluble sulfate, and the hydrocarbon portion of the molecule remained essentially intact as monohydroxybiphenyl. Kilbane, J.J., Resour. Cons. Recycl. 3:69-79 (1990), the teachings of which are incorporated herein by reference.

Kilbane has also isolated a mutant strain of *Rhodococcus* from this mixed bacterial culture. This mutant, IGTS8 or ATCC No. 53968, is a particularly preferred biocatalyst for use with the instant invention. The isolation and characteristics of this mutant are described in detail in J.J. Kilbane, U.S. Patent No. 5,104,801, the teachings of which are incorporated herein by reference. This microorganism has been deposited at the American Type Culture Collection (ATCC), 12301 Park Lawn Drive, Rockville, Maryland, U.S.A. 20852 under the terms of the Budapest Treaty, and has been designated as ATCC Deposit No. 53968.

One suitable ATCC No. 53968 biocatalyst preparation is a culture of the living microorganisms, prepared generally as described in U.S. Patent No. 5,104,801 and mutants or derivatives thereof (see, e.g. U.S. Patent. No. 5,358,869). Cell-free enzyme preparations obtained from ATCC No. 53968 or mutants thereof generally as described in U.S. Patent Nos. 5,132,219, 5,344,778 and 5,358,870 can also be used. These enzyme preparations can further be purified and employed.

Other examples of microorganisms that appear to behave in the same or similar manner include the microbial consortium (a mixture of several microorganisms) disclosed in Kilbane (1990), 3 Resour. Conserv. Recycl. 69-79, the microorganisms disclosed by Kilbane in U.S. Patent Nos. 5,002,888 (issued Mar. 26, 1991), 5,104,801 (issued Apr. 14, 1992), 5,344,778, 5,132,219, 5,198,341, 5,344,778, 5,356,813, 5,356,801, 5,358,869, 5,358,870 [also described in Kilbane (1990), *Biodesulfurization: Future Prospects in Coal Cleaning*, in Proc, 7th Ann. Int'l. Pittsburgh Coal Conf. 373-382], and 5,198,341 (issued Mar. 30, 1993); and by Omori *et al.* (1992), *Desulfurization of dibenzothiophene by Corynebacterium sp. strain SY1*, 58 Appl. Env. Microbiol. (No. 3) 911-915; and Izumi *et al.*, *Applied and Environmental Microbiology 60*:223-226 (1994) all incorporated herein by reference.

Each of the foregoing microorganisms can function as a biocatalyst in the present invention because each produces one or more enzymes (protein biocatalysts) that carry out the specific chemical reaction(s) by which sulfur is excised from refractory organosulfur compounds. Mutational or genetically engineered derivatives of any of the foregoing microorganisms, as exemplified by the U.S. patents listed above, can also be used as the biocatalyst herein, provided that appropriate biocatalytic function is retained.

Additional microorganisms suitable for use as the biocatalyst or biocatalyst source in the desulfurization process now described can be derived from naturally occurring microorganisms by known techniques. As set forth above, these methods include culturing preparations of microorganisms obtained from natural sources such as sewage sludge, petroleum refinery wastewater, garden soil, or coal, tar-contaminated soil under selective culture conditions in which the microorganisms are grown in the presence of refractory organosulfur compounds such as sulfur-bearing heterocycles as the sole sulfur source; exposing the microbial preparation to chemical or physical mutagens; or a combination of these methods. Such techniques are recounted by Isbister and Doyle in U.S. Patent No. 4,562,156 (issued Dec. 31, 1985); by Kilbane in 3 Resour. Conserv. Recycl. 69-79 (1990), U.S. Patent Nos. 5,002,888, 5,104,801 and 5,198,341; and by Omori and coworkers in 58 Appl. Env. Microbiol. (No. 3) 911-915 (1992), all incorporated by reference.

As explained above, enzymes are protein or peptide biocatalysts which can be made by living cells. Enzymes promote, direct or facilitate the occurrence of a specific chemical reaction or series of reactions (referred to as a pathway), generally, without themselves becoming consumed as a result thereof. Enzymes can include one or more unmodified or post-translationally or synthetically modified polypeptide chains or fragments or portions thereof, which catalyze the desired reaction or series of reactions when in the presence of the appropriate additional coenzymes, cofactors, or coreactants. The reaction or series of reactions relevant to one embodiment of the present invention culminates in the excision of sulfur from the hydrocarbon framework of a refractory organosulfur compound, such as a sulfur-bearing heterocycle. The hydrocarbon framework of the former refractory organosulfur compound

remains substantially intact. Microorganisms or enzymes employed as biocatalysts in the present invention preferably and advantageously do not consume the hydrocarbon framework of the former refractory organosulfur compound as a carbon source for growth. As a result, the fuel value of substrate fossil fuels exposed to BDS treatment does not deteriorate.

Although living microorganisms (e.g., a culture) can be used as the biocatalyst herein, this is not required. Biocatalytic enzyme preparations that are useful in the present invention include microbial lysates, extracts, fractions, subfractions, or purified products obtained by conventional means and capable of carrying out the desired biocatalytic function. Generally, such enzyme preparations are substantially free of intact microbial cells. Kilbane and Monticello disclose enzyme preparations that are suitable for use herein in U.S. Patent No. 5,132,219 (issued Jul. 21, 1992), and 5,358,870 (filed Jun. 11, 1992), for example. Rambosek *et al.* disclose recombinant microorganisms and enzyme preparations, engineered from *Rhodococcus* sp. ATCC No. 53968 and suitable for use herein, in U.S. Patent 5,356,813. In a particularly preferred embodiment, the biocatalyst is overexpressed in the recombinant host cell (such as a cell which contains more than one copy of the gene or genes). For example, The desulfurization of dibenzothiophene by *Rhodococcus* sp. IGTS8 has been shown to involve at least three enzymes (designated DszA, B and C), of which DszA and C are now appreciated to be monooxygenases. As such, in a particularly preferred embodiment, the biocatalyst includes one or more of the enzymes, Dsz A, Dsz B and/or Dsz C.

Enzyme biocatalyst preparations suitable for use herein can optionally be affixed to a solid support, e.g., a membrane, filter, polymeric resin, glass particles or beads, or ceramic particles or beads. The use of immobilized enzyme preparations facilitates the separation of the

biocatalyst from the reaction medium, such as the treated fossil fuel which has been depleted of refractory organosulfur compounds.

The specific activity of a given biocatalyst is a measure of its biocatalytic activity per unit mass. Thus, the specific activity of a particular biocatalyst depends on the nature or identity of the microorganism used or used as a source of biocatalytic enzymes, as well as the procedures used for preparing and/or storing the biocatalyst preparation. The concentration of a particular biocatalyst can be adjusted as desired for use in particular circumstances. For example, where a culture of living microorganisms (e.g., ATCC No. 53968) is used as the biocatalyst preparation, a suitable culture medium lacking a sulfur source other than sulfur-bearing heterocycles can be inoculated with suitable microorganisms and fermented until a desired culture density is reached. The resulting culture can be diluted with additional medium or another suitable buffer, or microbial cells present in the culture can be retrieved e.g., by centrifugation, and resuspended at a greater concentration than that of the original culture. The concentrations of microorganism and enzyme biocatalyst can be adjusted similarly. In this manner, appropriate volumes of biocatalyst preparations having predetermined specific activities and/or concentrations can be obtained.

As set forth above, a protein (designated DszD) has now been purified from *Rhodococcus* sp. IGTS8 which activates and enhances the activity of two monooxygenases integral in the biodesulfurization pathway (DszC and DszA). The function of this protein is believed to couple the oxidation of NADH with the oxygenation of the substrate molecules by DszA and DszC.. A search of the sequence databases revealed that DszD is equivalent to another recently isolated *Rhodococcus* protein, ThcE, which is reported to be induced by growth in the presence of atrazine, thiocarbamate herbicides and

primary alcohols. ThcE is a member of the group III alcohol dehydrogenases, or oxidoreductases, designated alcohol: N,N'-dimethyl-3-nitrosoaniline oxidoreductases and has been described in Nagy *et al.*, *Arch. Microbiol* (1995) *163*: 439-446, which is incorporated herein by reference in its entirety. DszD has a monomer molecular weight of approximately 50,000 (by SDS-PAGE) but behaves as a multimeric protein (decamer) on HPLC size exclusion chromatography. The activation of DszC and A by DszD follows saturation kinetics.

In view of the above described discovery, desulfurization of DBT can be enhanced by the addition of an oxidoreductase. Suitable oxidoreductases include monooxygenase reductases, or alcohol oxidoreductases, such as N,N'-dimethyl-4-nitrosoaniline (NDMA)-dependent alcohol oxidoreductases (MNO). Group III alcohol dehydrogenases, or oxidoreductases, have been reported to oxidize a primary alcohol and reduce an electron acceptor, such as the non-physiological compound NDMA. They generally contain a tightly but non-covalently bound molecule of NAD^+, which mediates electron transfer between an alcohol and the electron acceptor (e.g., NDMA). The term oxidoreductase is defined herein to include endogenous or wild-type enzymes, recombinantly produced enzymes, fusion proteins, active fragments, mutants or combinations thereof which possess the ability to enhance and/or activate the activity of DszA and/or DszC. Mutants include allelic variants, amino acid or site-directed mutations or derivatives (such as those prepared employing recombinant DNA technology). Alternatively mutants can be made employing other chemical or physical mutagenesis techniques with the host microorganism. The enzyme is preferably isolated from *Rhodococcus* or of rhodoccocal origin, such as IGTS8 or *Rhodococcus* sp. N186/21. Other preferred embodiments include recombinant oxidoreductases having an amino acid

sequence highly homologous (such as, atleast about 90%) to the amino acid sequence of these enzymes. Alternatively homologous oxidoreductases, such as those which can be isolated from *Amycolatopsis methanolics* and *Mycobacterium gastri* can be employed.

As set forth above, oxidoreductases which can be employed herein include those generally known in the art and can be used directly as found in nature (e.g., a microbial fraction which contains the protein or enzyme), obtained commercially or can be made recombinantly. For example, the DNA and amino acid sequences of DszD is set forth in Nagy *et al.*, *Arch Microbiology* (1995) *163*:439-446 (and illustrated in Figure 6) and can be used to transform a suitable host microorganism as is well known in the art and discussed in U.S. Patent No. 5,356,801, for example. The DNA sequence can be isolated from a suitable *Rhodococcus* employing well known techniques, such as PCR.

In another embodiment, the oxidoreductase can be overexpressed by the desulfurization microorganism (such as IGTS8). This can be accomplished, for example, by mutagenesis. Suitable mutagens include radiation, e.g., ultraviolet radiation, and chemical mutagens, such as N-methyl-N'-nitrosoguanidine, hydroxylamine, ethylmethanesulfonate and nitrous acid. The mutagenesis and subsequent screening for mutants harboring increased enzymatic activity can be conducted according to methods generally known in the art.

Where the oxidoreductase is recombinant, the protein can be made and, preferably, overexpressed *in situ*, such as by the addition of a recombinant microorganism which contains one or more copies of a DNA sequence which encodes the oxidoreductase. In a particularly preferred embodiment, the recombinant microorganism encoding the oxidoreductase also possesses one or more enzymes capable of catalyzing one or more reactions in the biodesulfurization of a fossil

fuel, particularly DszA and/or DszC. For example, the DNA encoding oxidoreductase, under control of a suitable promoter, can be transformed into IGTS8 or another microorganism capable of desulfurizing a fossil fuel. In another example, the DNA encoding the oxidoreductase is simultaneously (e.g., presented in a single plasmid or vector) or independently transformed into a common host cell with the DNA encoding the desulfurization biocatalyst(s) or enzymes. The DNA encoding the oxidoreductase can be, for example, under the control of the same or different promoter as the DNA encoding the biocatalyst capable of desulfurizing the fossil fuel. In one embodiment, the oxidoreductase DNA is incorporated or ligated into the desulfurization gene cluster or operon of IGTS8.

The oxidoreductase is added to the reaction mixture in a rate-enhancing amount. "Rate-enhancing amount," as defined herein, is an amount which will significantly increase the rate of reaction of the biocatalyst, as originally obtained, including activating the biocatalyst. For example, where the biocatalyst is IGTS8, a cell-free fraction or purified enzyme preparation thereof, a "rate-enhancing amount" of oxidoreductase is an amount of oxidoreductase that, in addition to that inherently present in the biocatalyst as obtained, will significantly increase the rate of desulfurization. The rate of desulfurization can be increased, for example, by at least 25%, 50% or 100% in comparison to the rate employing the biocatalyst per se. In one embodiment, the oxidoreductase is added to the reaction medium in an amount which achieves or approximates saturation kinetics.

The microorganism harboring the DNA sequence which encodes DszD can be grown under conditions which maximize the expression of the gene. *Rhodococcus* species which contain the gene can be grown in the presence of an alcohol (such as ethanol, ethanolamine, glycerol or

propanol), aldehydes (such as, propionaldehyde), thiocarbamates or atrazine, for example. These compounds may induce or increase the expression of the gene in the microorganism.

As summarized above, the invention described herein relates in one aspect to a DNA molecule or fragment thereof containing a gene or genes which encode an oxidoreductase and/or a biocatalyst capable of desulfurizing a fossil fuel that contains organosulfur compounds. The DNA molecule or fragment thereof can be purified and isolated DNA obtained from, e.g., a natural source, or can be recombinant (heterologous or foreign) DNA that is, e.g., present in a non-human host organism. The DNA can be isolated by well knwon techniques, such as PCR, designing oligonucleotide primers from the nucleotide sequence set forth in Figure 6.

The recombinant DNA molecules of the present invention include DNA resulting from the insertion into its chain, by chemical or biological means, of one or more genes encoding a biocatalyst capable of selectively cleaving carbon-sulfur bonds and an oxidoreductase, said gene not originally present in that chain. Recombinant DNA includes any DNA synthesized by procedures using restriction nucleases, nucleic acid hybridization, DNA cloning, DNA synthesis or any combination of the preceding. Methods of construction can be found in Maniatis *et al.*, and in other methods known by those skilled in the art.

Procedures for the construction of the DNA plasmids or vectors of the present invention include those described in Maniatis *et al.* and other methods known by those skilled in the art. The terms 'DNA plasmid" and "vector" are intended to encompass any replication competent plasmid or vector capable of having foreign or exogenous DNA inserted into it by chemical or biological means and subsequently, when transformed into an appropriate non-human host organism, of expressing the product of the foreign or exogenous DNA

insert (e.g., of expressing the biocatalyst and oxidoreductase of the present invention). In addition, the plasmid or vector must be receptive to the insertion of a DNA molecule or fragment thereof containing the gene or genes of the present invention, said gene or genes encoding a biocatalyst, as defined above. Procedures for the construction of DNA plasmid vectors include those described in Maniatis *et al.* and others known by those skilled in the art.

The plasmids of the present invention include any DNA fragment containing a gene or genes encoding an oxidoreductase and/or a biocatalyst. The term "plasmid" is intended to encompass any DNA fragment. The DNA fragment should be transmittable, for example, to a host microorganism by transformation or conjugation. Procedures for the construction or extraction of DNA plasmids include those described in Maniatis *et al.* and others known by those skilled in the art.

The transformed non-human host organisms of the present invention can be created by various methods by those skilled in the art. For example, electroporation as explained by Maniatis *et al.* can be used. By the term "non-human host organism" is intended any non-human organism capable of the uptake and expression of foreign, exogenous or recombinant DNA. Preferably, the host organism is a bacterium, more preferably a pseudonomad.

In the biocatalytic desulfurization stage, the carbonaceous material or fossil fuel containing sulfur-bearing heterocycles is combined with the biocatalyst and oxidoreducase. The relative amounts of biocatalyst and oxidoreducase and carbonaceous material, such as a fossil fuel, can be adjusted to suit particular conditions, or to produce a particular level of residual sulfur in the treated, desulfurized material. The amount of biocatalyst preparation to be combined with a given quantity of

substrate will reflect the nature, concentration and specific activity of the particular biocatalyst(s) and oxidoreductase used, as well as the nature and relative abundance of inorganic and organic sulfur compounds present in the substrate and the degree of desulfurization sought or considered acceptable.

The method of desulfurizing a fossil fuel of the present invention involves two aspects. First, a host organism or biocatalytic preparation obtained therefrom and oxidoreductase is contacted with a fossil fuel to be desulfurized. This can be done in any appropriate container, optionally fitted with an agitation or mixing device. The mixture is combined thoroughly and allowed to incubate for a sufficient time to allow for cleavage of a significant number of carbon-sulfur bonds in organosulfur compounds, thereby producing a desulfurized fossil fuel. In one embodiment, an aqueous emulsion or microemulsion is produced with an aqueous culture of the organism or enzyme fraction and the fossil fuel, allowing the organism to propagate in the emulsion while the expressed biocatalyst cleaves carbon-sulfur bonds.

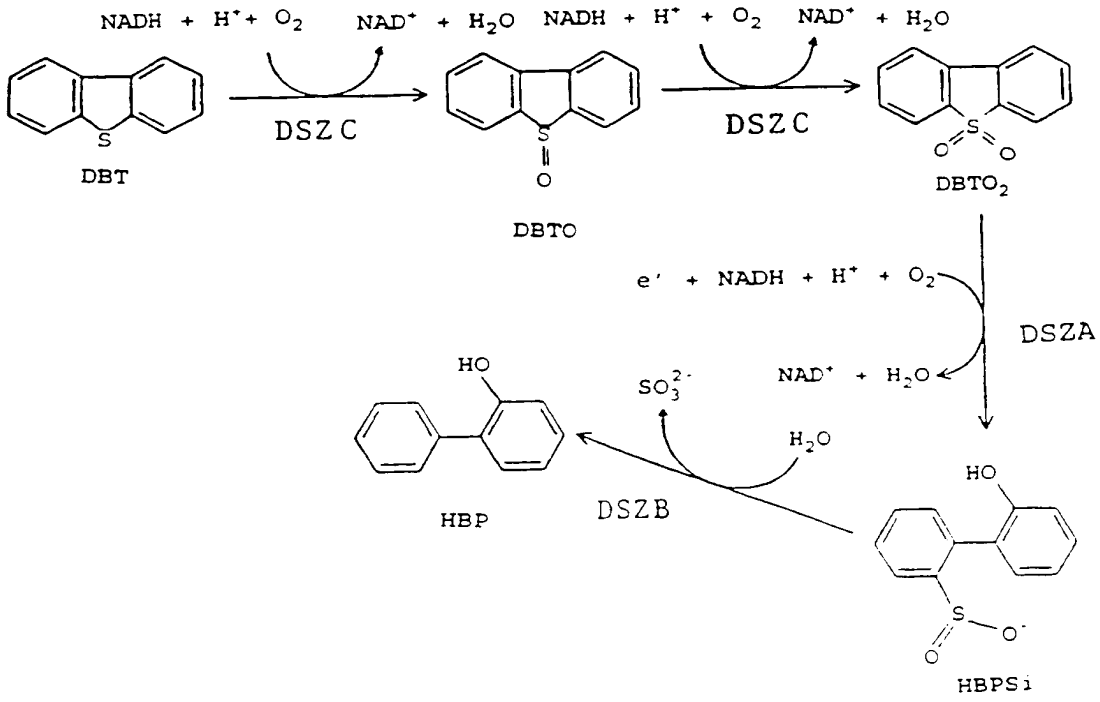
Variables such as temperature, mixing rate and rate of desulfurization will vary according to the organism biocatalyst and/or oxidoreductase, used. The parameters can be determined through no more than routine experimentation.

Several suitable techniques for monitoring the rate and extent of desulfurization are well-known and readily available to those skilled in the art. Baseline and time course samples can be collected from the incubation mixture, and prepared for a determination of the residual organic sulfur in the fossil fuel. The disappearance of sulfur from organosulfur compounds, such as DBT, in the sample being subjected to biocatalytic treatment can be monitored using, e.g., X-ray fluorescence (XRF) or atomic

emission spectrometry (flame spectrometry). Preferably, the molecular components of the sample are first separated, e.g., by gas chromatography.

The process and the biocatalytic compositions (including the recombinant microorganisms) of the claimed invention result in a significant and unexpected improvement over earlier disclosed processes of desulfurization. It has been shown that *in vitro* the reactions catalyzed by purified DszA and DszC proteins are activated by the addition of the oxidoreductase. This is particularly unexpected in view of recent discussions in the literature suggesting that FAD binds directly to DszC (Denome et al., J. Bacteriol., 176:6707-6716, 1994) and the suggestion that NADH is the only cofactor required for the system (Ohshiro et al., FEMS Microbiol. Lett. 118:341-344, 1994). Others suggest that DszABC are the sole enzymes responsible for desulfurization to occur (Piddington, et al., Appl. Env. Microbiol., 67:468-475, 1995).

Without being limited to any particular mechanism or theory, it is believed that the pathway of the desulfurization reaction is set forth below:



Here, the oxidoreductase is believed to be a short electron transport chain to deliver the reducing equivalents from NADH (or other electron donor) to the enzymes, DszC and/or DszA (possibly a physiological electron acceptor of the oxidoreductase). The enzyme DszC is believed to be responsible for the biocatalysis of the oxidation reaction of DBT to DBTO2. The enzyme DszA is believed to be responsible for the oxygenation of DBTO2 to phenolphenylsulfite (PPS).

It is particularly preferred to add the cofactor, FMN, to the reaction medium as well as an electron donor, NADH or NADPH. Also preferred is the addition of an NADH or NADPH regeneration system for converting NAD+ to NADH, according to methods known in the art.

The invention will now be further illustrated by the way of the following examples.

EXEMPLIFICATION

Growth of *Rhodococcus* sp. IGTS8:

A sample of frozen stock of *Rhodococcus* sp. IGTS8 strain CPE-648 containing plasmid pENOK3 (genotype of DszA-B-C+) as described by Piddington *et al.*(*Appl. Environ. Microbiol. 61*:468-475 (1995)) was grown in 500 ml of rich medium in a 2000 ml shake flask for 48 hours at 30°C. This culture was used to inoculate (4% inoculum) a 15 Liter NBS fermentater in the same medium. This culture was grown for 48 hours at 30°C while controlling pH (between 6.8 and 7.3), agitation and dissolved oxygen (>50% saturated). Finally a 5% inoculum was transferred to a production-scale fermentater (300 Liter Chemap) containing basal salts medium, 0.5 g/L Ivanhoe antifoam, 8 g/l ethanol and 1.5 mM dimethyl sulfoxide. The culture was grown for 45 hours, achieving an optical density of 11, with a doubling time of

4.3 hours during the first 24 hours of the run. The cell suspension was concentrated through a Westfalia centrifuge resulting in the production of about 2.5 kg. of wet cell paste. The paste was stored at -70°C until used for purification.

Purification of DszD

150 g (wet cell paste) of the *Rhodococcus* as grown above were resuspended in 25 mM NaPi, pH 7.5 (buffer A) containing 100 mM NaCl, 0.5 mM DTT, 1' mM PMSF and DNAse. The cell suspension was passed two times through a French pressure cell (at 20,000 psi) and then centrifuged at 30,000 x g for 45 minutes (5°C) to remove unbroken cells and cell debris. All subsequent chromatography steps were performed at 4°C using a Pharmacia FPLC system. The supernatant was loaded into a Q-sepharose column (2.6 cm x 20 cm) equilibrated with buffer A containing 100 mM NaCl. Following loading the column was washed extensively with the same buffer until the OD280 of the eluent was close to zero. The column was developed with a linear gradient from 100 mM NaCl to 500 mM NaCl in buffer A for 180 minutes at a flow rate of 5 mL/minute and 10 mL fractions were collected. The fractions which displayed DszD activity were pooled and dialyzed overnight vs. buffer A. The dialysate was loaded onto a Toyopearl DEAE-650M column (2.6 cm x 10 cm) equilibrated with buffer A. The column was developed with a linear gradient from 0 to 200 mM NaCl for 90 minutes at a flow rate of 4 mL/minute and 4 mL fractions were collected. The fractions which contained DszD activity were pooled and dialyzed overnight vs. buffer A. The dialysate was loaded onto a Pharmacia MonoQ column equilibrated with buffer A. The column was developed with a linear gradient from 160 to 300 mM NaCl for 30 minutes at a flow rate of 0.5 mL/minute and 0.5 mL fractions were collected. The fractions which displayed DszD activity were pooled and concentrated to 0.2

mL using Amicon microconcentrators (molecular weight cutoff of 10 kDa). The concentrated sample was then applied to a Pharmacia Superdex 75 size exclusion column equilibrated with buffer A containing 100 mM NaCl. The column was eluted with the same buffer at a flow rate of 0.2 mL/minute and 0.2 mL fractions were collected. The fractions containing DszD activity were pooled and concentrated using the microconcentrators and the protein was stored on ice until used. SDS-PAGE analysis (14% polyacrylamide) of the final preparation showed a single band with an approximate monomer molecular weight of 50,000 Da.

Enzyme assays

DszD activity was measured by monitoring DBTO and DBTO2 production from DBT as catalyzed by the combination of DszC and DszD. The DszC was obtained from an *E. coli* expression system, previously described. The assay (in 25 mM NaPi pH 7.5, 100 mM NaCl and 0.5 mM DTT) contained DszC (between 6 and 15 μg), 3 mM NADH, 10 μM FMN, 100 μM DBT and the sample containing DszD. The assay mixture was allowed to incubate at 30°C with shaking at 300 rpm for some period of time (typically 15 to 60 minutes). The reaction was stopped by the addition of acetonitrile (to 50%) and the products analyzed by reversed phase HPLC. Activation of DszA by DszD was assayed in the same manner (DszA was also obtained from an *E. coli* expression system) except that the substrate was DBT sultone and the product was 2,2'-dihydroxybiphenyl (BHBP).

Results:

Purification of DszD

Figure 1 shows the DszD activity profile of the fractions from the first anion exchange column (Q-sepharose). As can be seen by these data the activity starts around fraction 20 and extends to about fraction 60.

Both DszA and C activation occurs in these reactions, furthermore the endogenous DszC activity is also present in these fractions (notably fractions 40 to 50). Fractions 40 to 60 were pooled and further separated on Toyopearl - DEAE. An activity pattern similar to the Q-sepharose column was observed after the Toyopearl - DEAE chromatography except that the activity eluted at a lower salt concentration and endogenous DszC activity occurred in later fractions (a small amount of activity in fraction 40). This was further substantiated by Western analysis which showed that DszC eluted with a peak between fraction 45 and 50 (data not shown). Fractions 15 to 35 were pooled and applied to the MonoQ column. The active fractions from this column were pooled, concentrated and further separated by chromatography over a Superdex 75 FPLC column. The activity profile of this column is shown in Figure 2. This figure shows that both DszA and C are activated by protein(s) in the same fractions. SDS-PAGE analysis (Figure 3) showed that the final preparation consisted of a single polypeptide of molecular weight approximately 50,000. HPLC analysis using a TosoHaas TSK3000SW size exclusion column on a Hewlett Packard 1050 HPLC system showed a single protein peak eluted at an approximate mass of 500,000 Da indicating that the native protein is most likely a decamer.

<u>DszD activation of DszC and DszA</u>

Figure 4 shows that the activation of DszC by DszD follows saturation kinetics. As the ratio between DszD and C is increased an increased rate of DBTO2 formation is observed. A plot of the initial rate vs. DszD:DszC shows that saturation is achieved. Figure 5 shows the result of activation of DszA by the same preparation. The same effect is observed, i.e. as more DszD is added an increase in the DszA reaction rate occurs.

Amino acid sequence of DszD

DszD was subjected to N-terminal sequence and the following sequence was obtained (one letter amino acid abbreviations):

H2N-AIELNQIWDFPIKEFHPFPRALMGVGAHDIIGVEAKNLGFKRTLLM-COOH
(SEQ ID. NO: 3)

A search of the data-bases resulted in a 100% match with a *Rhodococcus* protein designated ThcE (Nagy *et al.*, *Arch. Microbiol.* *163*:439-446 (1995)). The DNA sequence and putative amino acid sequences of the open reading frames are set forth in Figure 6. This protein has high homology to the alcohol: N,N'-dimethyl-4-nitrosoaniline (NDMA) oxidoreductses found in other Gram-positive organisms which are involved in the oxidation of alcohols and the concomitant reduction of an electron acceptor. The physiological electron acceptor in those organisms is unknown.

EQUIVALENTS

Those skilled in the art will know, or be able to ascertain, using no more than routine experimentation, many equivalents to the specific embodiments of the invention described herein. These and all other equivalents are intended to be encompassed by the following claims.

CLAIMS

1. A method for enhancing the rate of biodesulfurization of a fossil fuel containing organic sulfur compounds, comprising the steps of:

a) contacting the fossil fuel with an aqueous phase containing a biocatalyst capable of cleaving carbon-sulfur bonds and a rate-enhancing amount of an oxidoreductase, thereby forming a fossil fuel and aqueous phase mixture;

b) maintaining the mixture of step a) under conditions sufficient for cleavage of the carbon-sulfur bonds of the organic sulfur molecules by the biocatalyst, thereby resulting in a fossil fuel having a reduced organic sulfur content; and

c) separating the fossil fuel having a reduced organic sulfur content from the resulting aqueous phase.

2. The method of Claim 1 wherein the oxidoreductase is a type III alcohol dehydrogenase.

3. The method of Claim 1 wherein the oxidoreductase is N,N'-dimethyl-4-nitrosoaniline-dependent alcohol oxidoreductase.

4. The method of Claim 1 wherein the oxidoreductase is of *Rhodococcus* origin.

5. The method of Claim 4 further comprising adding NADH or NADPH and flavin.

6. The method of Claim 5 wherein the fossil fuel is a liquid hydrocarbon.

7. The method of Claim 4 wherein the cleavage of the carbon-sulfur bonds is performed by an oxidative pathway.

8. The method of Claim 7 wherein the biocatalyst capable of cleaving carbon-sulfur bonds is a microorganism.

9. The method of Claim 8 wherein the microorganism contains a recombinant DNA molecule which encodes one or more enzymes capable of cleaving carbon-sulfur bonds.

10. The method of Claim 9 wherein the recombinant DNA molecule is derived from *Rhodococcus* sp. ATCC 53968.

11. The method of Claim 7 wherein the biocatalyst capable of cleaving carbon-sulfur bonds is a cell-free fraction.

12. The method of Claim 11 wherein the biocatalyst is a cell-free fraction of *Rhodococcus* sp. ATCC 53968.

13. The method of Claim 7 wherein the biocatalyst comprises one or more enzymes or enzyme fractions derived from a microorganism having the capability of cleaving carbon-sulfur bonds.

14. The method of Claim 13 wherein the microorganism is *Rhodococcus* sp. ATCC 53968.

15. The method of Claim 7 wherein the biocatalyst capable of cleaving carbon sulfur bonds and oxidoreductase are recombinantly produced by a single microorganism.

16. A DNA molecule comprising DNA which encodes an oxidoreductase and DNA which encode a biocatalyst capable of desulfurizing a fossil fuel which contains organic sulfur molecules.

17. The DNA molecule of Claim 16 wherein the oxidoreductase is a type III alcohol dehydrogenase.

18. The DNA molecule of Claim 16 wherein the oxidoreductase is N,N'-dimethyl-4-nitrosoaniline-dependent alcohol oxidoreductase.

19. The DNA molecule of Claim 16 wherein the ocidoreductase is of *Rhodococcus* origin.

20. The DNA molecule of Claim 19 wherein the DNA molecule which encodes the biocatalyst is derived from *Rhodococcus* sp. ATCC 53968.

21. A microorganism containing a recombinant DNA molecule which encodes:
a) an oxidoreductase; and
b) one or more biodesulfurization enzymes.

22. The microorganism of Claim 21 wherein the oxidoreducase is a type III alcohol dehydrogenase.

23. The microorganism of Claim 21 wherein the oxidoreductase is N,N'-dimethyl-4-nitrosoaniline-dependent alcohol oxidoreductase.

24. The microorganism of Claim 21 wherein the DNA which encodes the oxidoreductase is of *Rhodococcus* origin.

25. The microorganism of Claim 24 wherein the DNA which encodes one or more biodesulfurization enzymes is derived from *Rhodococcus* sp. ATCC 53968.

26. A composition comprising:
a) an oxidoreductase; and
b) a biocatalyst capable of desulfurizing a fossil fuel which contains organic sulfur molecules.

27. The composition of Claim 26 wherein the oxidoreductase is a type III alcohol dehydrogenase.

28. The composition of Claim 26 wherein the oxidoreductase is N,N'-dimethyl-4-nitrosoaniline-dependent alcohol oxidoreductase.

29. The composition of Claim 26 wherein the DNA which encodes the oxidoreductase is of *Rhodococcus* origin.

30. The composition of Claim 29 wherein the biocatalyst is *Rhodococcus* sp. ATCC 53968 or enzymes thereof.

31. The composition of Claim 27 further comprising flavin and NAD or NADH.

32. A method for enhancing the rate of reaction of a carbonaceous material containing organic sulfur compounds, comprising the steps of:
a) contacting the material with an aqueous phase containing a biocatalyst capable of oxidizing carbon-sulfur bonds and a rate-enhancing amount of an oxidoreductase;
b) maintaining the mixture of step a) under conditions sufficient for reaction of the organic sulfur compounds by the biocatalyst.

33. The method of Claim 32 wherein the oxidoreductase is a type III alcohol dehydrogenase.

34. The method of Claim 32 wherein the oxidoreductase is N,N'-dimethyl-4-nitrosoaniline-dependent alcohol oxidoreductase.

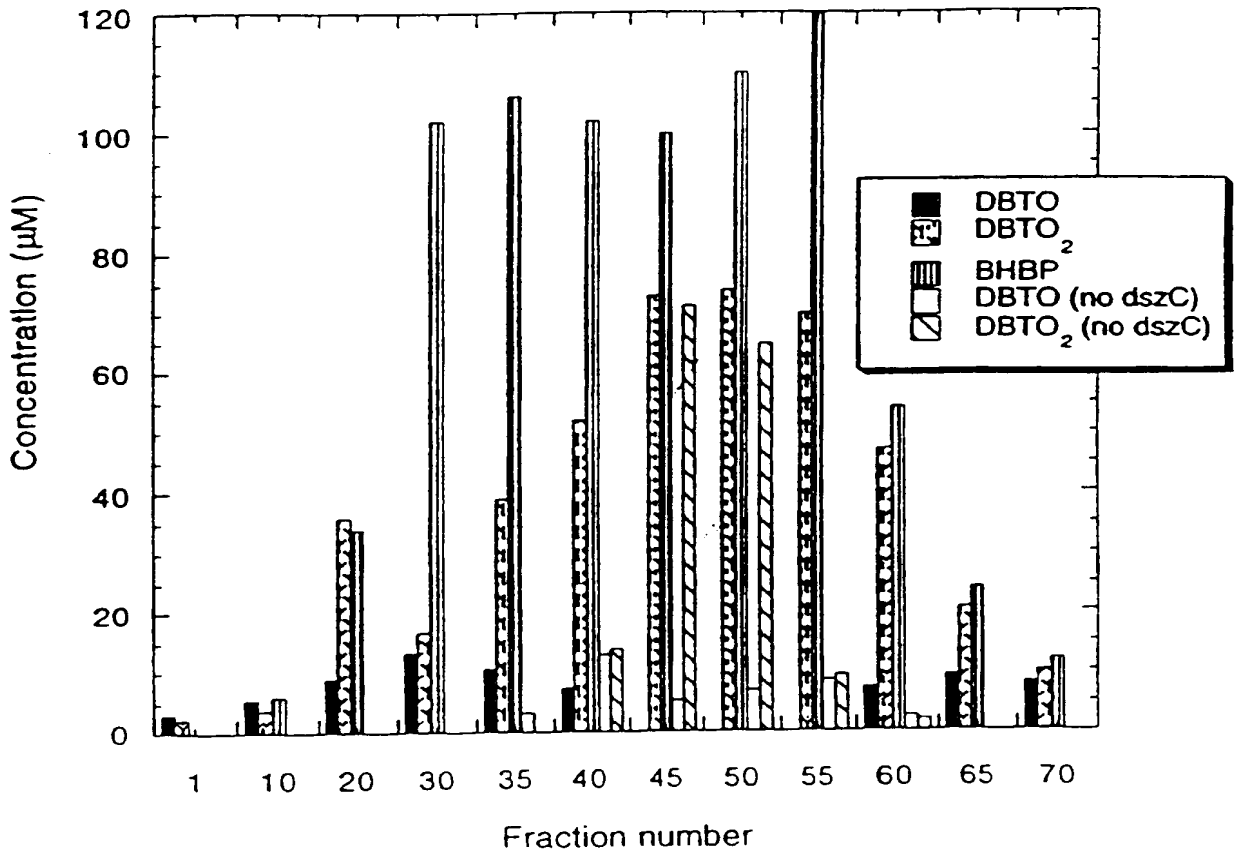
35. The method of Claim 32 wherein the oxidoreductase is of *Rhodococcus* origin.

36. The method of Claim 35 wherein the biocatalyst is a monooxygenase.

37. The method of Claim 35 wherein the biocatalyst is a DszA or DszC.

38. The method of Claim 37 further comprising adding NADH or NADPH and flavin.

39. The method of Claim 38 wherein the sulfur containing compound is a substituted or unsubstituted dibenzothiophene.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Fraction number
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DBTO (no dszC)
DBTO2 (no dszC)

FIGURE 1

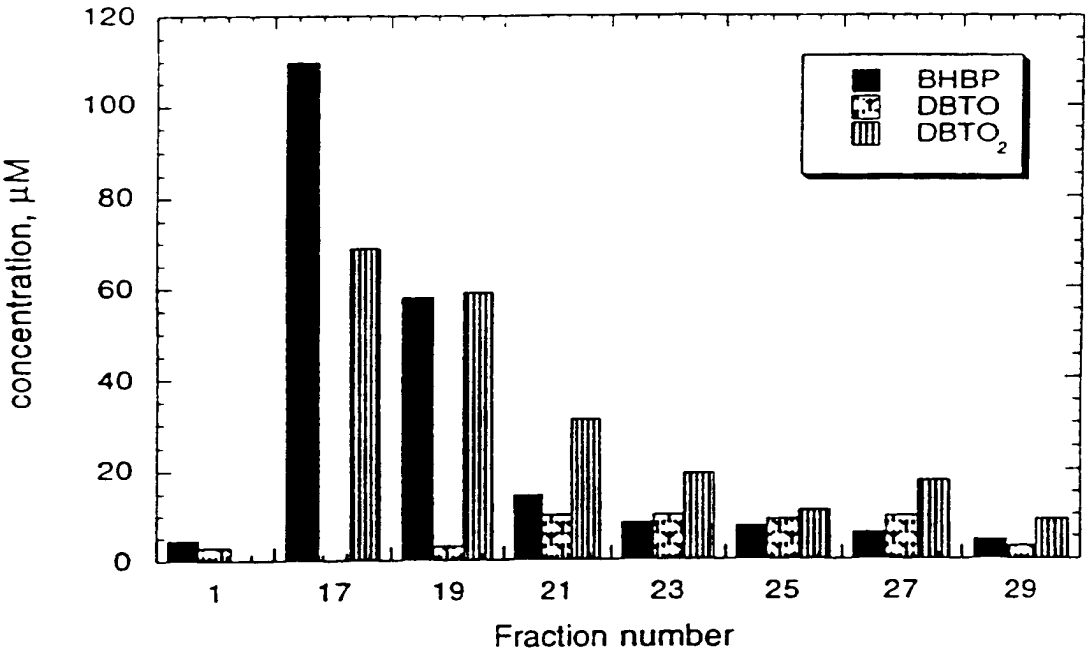

FIGURE 2

FIG. 3

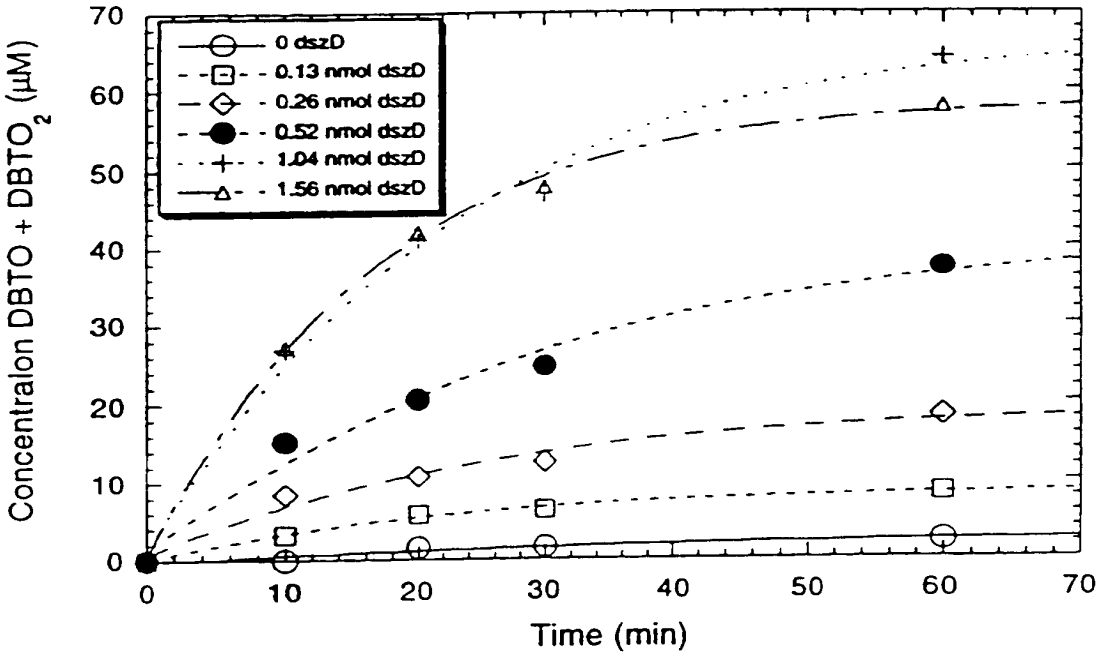

FIGURE 4

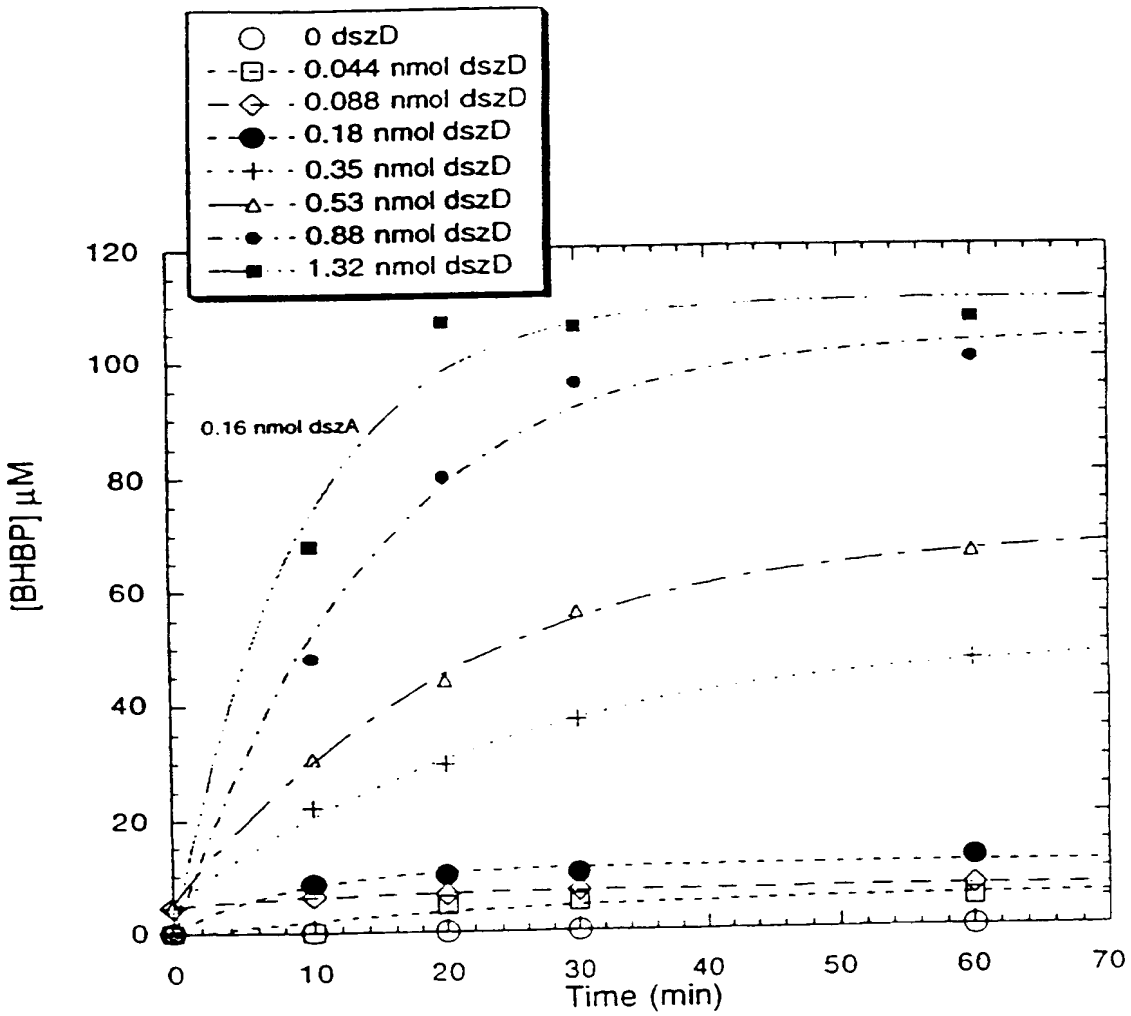

FIGURE 5

Protein sequence

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MNTKKYEGRGDVIKGDEKTVRAISEHIQDDWCTPGNPREVTVESMIPVVDHAINKSYF

DNA sequence base 946(a) to 1534

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Figure 6A

SUBSTITUTE SHEET (RULE 26)

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FIGURE 6B

INTERNATIONAL SEARCH REPORT

International Application No
PCT/US 95/15864

A. CLASSIFICATION OF SUBJECT MATTER
IPC 6 C12N15/53 C12N15/52 C12S1/02 C10G32/00 C12N1/21
C12N9/02 //(C12N1/21,C12R1:01,C12R1:19)

According to International Patent Classification (IPC) or to both national classification and IPC

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)
IPC 6 C12P C10G

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

Electronic data base consulted during the international search (name of data base and, where practical, search terms used)

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category *	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X	APPLIED ENVIRONMENTAL MICROBIOLOGY, vol. 61, February 1995, pages 468-475, XP002002386 C.S. PIDDINGTON ET AL : "Sequence and molecular characterization of a DNA region encoding the Dibenzothiophene desulfurization operon of Rhodococcus sp. strain IGTS8" cited in the application see the whole document --- -/--	16

[X] Further documents are listed in the continuation of box C.

[X] Patent family members are listed in annex.

* Special categories of cited documents :

"A" document defining the general state of the art which is not considered to be of particular relevance

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"P" document published prior to the international filing date but later than the priority date claimed

"T" later document published after the international filing date or priority date and not in conflict with the application but cited to understand the principle or theory underlying the invention

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"Y" document of particular relevance; the claimed invention cannot be considered to involve an inventive step when the document is combined with one or more other such documents, such combination being obvious to a person skilled in the art.

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Date of the actual completion of the international search
7 May 1996

Date of mailing of the international search report
23. 05. 96

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Le Cornec, N

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INTERNATIONAL SEARCH REPORT

International Application No
PCT/US 95/15864

C.(Continuation) DOCUMENTS CONSIDERED TO BE RELEVANT

Category *	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X A	FEMS MICROBIOLOGY LETTERS, vol. 118, 1994, pages 341-344, XP002002324 TAKASHI OHSHIRO ET AL: "Enzymatic desulfurization of Dibenzothiphene by a cell-free system of Rhodococcus erythroplis D-1" see the whole document	26

A	ARCHIVES OF MICROBIOLOGY, vol. 163, 1995, pages 439-446, XP002002388 I. NAGY ET AL: "Characterization of the Rhodococcus sp.NI86/21 gene encoding alcohol:N,N'dimethyl-4-nitrosoaniline oxidoreductase inducible by atrazine and thiocarbamate herbicides" cited in the application see abstract	16-25

A A	EP,A,0 445 896 (INSTITUTE OF GAS TECHNOLOGY) 11 September 1991 cited in the application see page 12 - page 13; claims	26

X A	BIOSCIENCE , BIOTECHNOLOGY , AND BIOCHEMISTRY, vol. 59, no. 7, July 1995, pages 1349-1351, XP002002325 TAKASHI OHSHIRO ET AL: "Involvement of Flavin coenzyme in dibenzothiophene degrading enzyme system from Rhodococcus erythropolis D-1" see the whole document	26

Form PCT/ISA/218 (continuation of second sheet) (July 1992)

INTERNATIONAL SEARCH REPORT

...information on patent family members

International Application No
PCT/US 95/15864

Patent document cited in search report	Publication date	Patent family member(s)		Publication date
EP-A-445896	11-09-91	US-A-	5132219	21-07-92
		AT-T-	126268	15-08-95
		CA-C-	2032939	27-06-95
		DE-D-	69111855	14-09-95
		DE-T-	69111855	11-01-96
		JP-B-	7071481	02-08-95
		US-A-	5344778	06-09-94
		US-A-	5358870	25-10-94